MEASUREMENT OF THE PARAMETERS OF 'GAS-SOLID PARTICLE' FLOWS BY OPTICAL METHODS

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16. Abstract

Mathematical relations are derived for obtaining local-number concentration or mass concentration of particles in two-phase flows from optical measurements based on the dependence of the intensity of scattered light on the properties of the scattering medium. Relations are also obtained for calculating the slip velocity of particles in a gas flow from laser Doppler measurements. An experimental device for obtaining all the data needed in determining the average characteristics of two-phase flows is described.

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MEASUREMENT OF THE PARAMETERS OF 'GAS-SOLID PARTICLE' FLOWS BY OPTICAL METHODS /384*

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Experimental studies of two-phase "gas-solid particle" flows involve measuring these parameters: mass flow of impurity $q_s = \rho_{sd}U_S$, local number concentration N_S (cm^{-3}), and mass concentration ρ_{sd} ($g \cdot cm^{-3}$) concentration of particles, and velocities of solid phase U_S and gas phase U_0. Probe methods [1, 2] can yield information only on the mass flow q_s and the velocity of the gas phase U_0, insufficient in setting up methods for calculating two-phase flows that allow for the relative motion of phases. The necessity of obtaining data on the local concentration ρ_{sd} and the velocity of solid-phase particles U_S was responsible for developing a method capable of filling the gap, and in several instances of completely replacing probe measurements. Besides their fundamental restrictions, probe measurements have several disadvantages involved with the perturbation of the test flows and the change in probe parameters in the course of measurements.

Measuring concentration of solid phase. To measure the local number or mass concentrations of particles in specific two-phase flows, an optical method can be used: it is based on the dependence of the intensity of scattered light on the properties of the scattering medium. In several cases this fact can be used in measuring the distribution field of the solid impurity in a two-phase flow.

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* Numbers in the margin indicate pagination in the foreign text.

When a parallel monochromatic beam of light with initial intensity I_0 is passed through a polydispersed medium with size distribution particle function $f_N(D)$, we can write

$$I(\beta) = I_0 N_S v \int_0^\infty \sigma(\varrho, \beta, m) f_N(D)\, dD, \tag{1}$$

for the intensity of light $I(\beta)$ scattered by a sufficiently small volume v at an angle β to the direction of propagation of the main beam, where $\sigma(\rho, \beta, m)$ is a function characterizing the scattering ability of the particles; D is particle size; $\varrho = \frac{\pi D}{\lambda}$ is the diffractional parameter; λ is the wavelength of the radiation; and m is the index of refraction of the particle substances.

In converting to the mass size distribution function $f_M(D)$, Eq. (1) becomes (it is assumed that the particles consist of the same material):

$$I(\beta) = I_0 \varrho_{sd} v \int_0^\infty \sigma(\varrho, \beta, m) f_M(D) \frac{dD}{D^3}. \tag{2}$$

Integration in Eqs. (1) and (2) proceeds over all particle sizes /385
in the volume v.

From Eqs. (1) and (2) it is clear that to determine ρ_{sd} from the measured quantities $I(\beta)$ and I_0 we need information on the functions $\sigma(\rho, \beta, m)$ and $f_M(D)$. In several particular cases, for example, for "gas-liquid" type two-phase flows containing spherical particles with $\rho \gg 1$, the function $\sigma(\rho, \beta, m)$ is known, and analysis of the scattering indicatrix in the region of small angles [4] enables us to determine the function $f_M(D)$ and the value of ρ_{sd}. When "gas-solid particle" flows are studied, the determination of ρ_{sd} or N_S from the measured $I(\beta)$ as a rule is not possible.

However, if during the passage of this kind of flow no deformation of the particle size distribution function occurs, it becomes possible to measure the relative concentrations, therefore the profiles of the relative distribution of the impurity in the flow. Accordingly, by Eq. (2) for two sufficiently small regions of a flow, whose size is determined by the cross section of the illuminating beam and the parameters of the receiving optical system, we can write

$$\frac{\varrho_{sd}(x_i y_i z_i)}{\varrho_{sd}(x_k y_k z_k)} = \frac{I^*(\beta, x_i y_i z_i)}{I^*(\beta, x_k y_k z_k)} \frac{I_0^*(x_k y_k z_k)}{I_0^*(x_i y_i z_i)}, \tag{3}$$

where x, y, z are the coordinates of the corresponding volume; I_0^* (x,y,z) is the intensity of the illuminating beam in the given volume; and I^* (β,x,y,z) is the intensity of the scatter of light.

When the profile of the relative concentration is measured along the x axis, Eq. (3) with reference to attenuation of the incident and scatter of radiation can be written thusly:

$$\frac{\varrho_{sd}(x)}{\varrho_{sd}(0)} = \frac{I^{**}(\beta, x)\exp\{-[\int_R^0 k(0, y)dy + \int_0^l k(0, y)dy]\}}{I^{**}(\beta, 0)\exp\{-[\int_{R_x}^0 k(x, y)dy + \int_0^{l_x} k(x, y)dy]\}}, \tag{4}$$

where $I^{**}(\beta$,x) is the intensity of the scattered light in the plane of the photodetector (PD); and k(x,y) is the coefficient of attenuation of the medium. The related symbols are shown in Fig. 1. Eq. (4) was obtained on the assumption that Bouguer's law is applicable to the test medium [5]. For small β situated in the yz plane, the difference in the attenuation along the sections (0, R_x) and (0, l_x) can be neglected. In this case Eq. (4) becomes:

$$\frac{\varrho_{sd}(x)}{\varrho_{sd}(0)} = \frac{I^{**}(\beta, x)\exp[-\int_R^R k(0, y)dy]}{I^{**}(\beta, 0)\exp[-\int_{R_x}^{R_x} k(x, y)dy]}. \tag{5}$$

In (5) the ratio of the exponential terms is equivalent to the ratio of the intensities of the illuminating beam after passing through the corresponding sections of the flow. Finally, we can write:

$$\frac{\varrho_{sd}(x)}{\varrho_{sd}(0)} = \frac{I^{**}(\beta,x)\,I_0^{**}(0)}{I^{**}(\beta,0)\,I_0^{**}(x)} \qquad (6)$$

where $I_0^{**}(0)$ is the intensity of the beam after traversing the section $(-R,R)$; $I_0^{**}(x)$ is the beam intensity after traversing the section $(-R_x, R_x)$.

When determining the profile of the relative concentration at corresponding points one measures the intensity of the scattered light $I^{**}(\beta,x)$ and the intensity of the attenuated illuminating beam $I_0^{**}(x)$ over the linear section of operation of the PD. The quantities $\frac{\varrho_{sd}(x)}{\varrho_{sd}(0)}$ are calculated by Eq. (6). Since I_0 does not appear in Eq. (6), in the simultaneous measurement of $I^{**}(\beta,x)$ and $I_0^{**}(x)$, a variation in the intensity of the radiation source during the experiment does not influence the end results of the calculations. It should be noted that converting from Eq. (5) to equality (6) is possible only if the PD recording the intensity of the direct attenuated beam is at the distance $L \gg \frac{a_0\bar{D}}{2\lambda}$ from the scattering volume; $\bar{D}$ is the mean impurity particle size; and a_0 is the size of the PD diaphragm. Here we can neglect the value of the light striking the PD and diffraction-scattered at small angles [6].

In Fig. 2 are presented the profiles of the relative concentration of particles of different sizes along the axis (a) and at the cross section z = 250 mm (b) of a turbulent two-phase stream. The local values of the impurity concentrations are related to the value on the flow axis in the initial section (a) and at z = = 250 mm (b). Al_2O_3 particles with a narrow particle size distribution function were used as the solid phase. Measurement of particle velocity with a LDIS [laser doppler interferometer system] [7] together with probe measurements of the mass flow

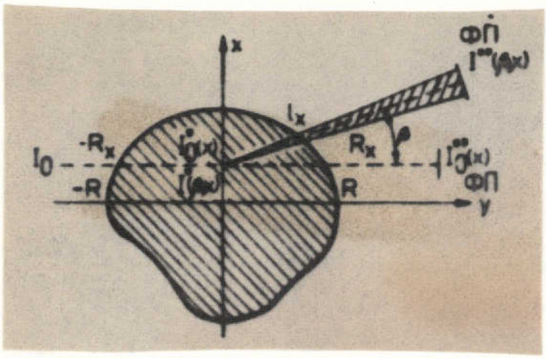

Fig. 1. Experimental geometry

made it possible to compare the data obtained by both methods. Good agreement in the results of measurements obtained by the independent methods was observed for test flows in the range of optical densities $0.1 \leqslant \tau \leqslant 5.0$ and in the particle size range 15 μm $\leqslant$ D $\leqslant$ 110 μm. The relative error of the optical method, /387

a b

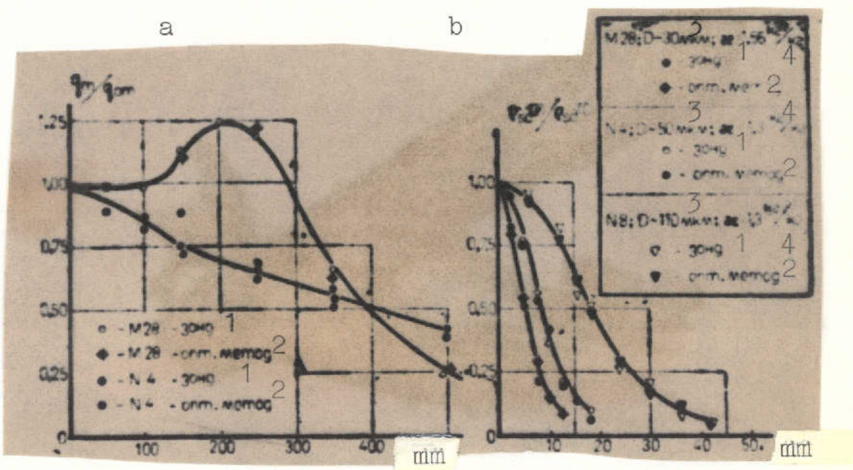

Fig. 2. Distribution of Al_2O_3 impurity along axis of two-phase flow (a): radial distribution of Al_2O_3 impurity of different grain size at the cross section z = 250 mm of the two-phase flow (b).
Key: 1. Probe
2. Optical method
3. μm
4. kg/kg

determined by comparing the mass flow calculated from the mass flow profiles with the total impurity mass flow did not exceed 13 percent. The data obtained show that (within the limits of this indicated error) the optical method of measuring the distribution of a solid impurity with a narrow particle size distribution function is representative for different types of two-phase flows.

Measurement of velocities of gas and of solid phases. The possibility of measuring the velocities of solid-phase particles by an optical method using a LDIS was shown in [7]. However, for the aerodynamics of two-phase flows it is important to determine not only the absolute particle velocity, but also the particle slip velocity relative to the carrier gas flow. In [8] a direct method of determining the slip velocity was proposed: it is based on analyzing the spectrum of the scatter radiation. Whereas in a flow, along with large solid-phase particles having the velocity U_S there are fine particles moving at a flow velocity U_0, the spectrum of scattered radiation $P(w)$ will contain two components at the frequencies w_s and w_0, respectively, which are determined by the particle velocities U_S and U_0:

$$P(w) = P_1(w) + P_2(w). \qquad (7)$$

When the particle size distribution function is narrow, the spectra $P_1(w)$ and $P_2(w)$ have maxima at the frequencies w_S and w_0 and the slip velocity is determined from the displacement $\Delta w = w_S - w_0$.

The simplicity of the method does not preclude the disadvantages associated with the difficulty of separating signals at low solid-phase particle slip velocities. This latter fact occurs not only for small gas phase velocities $U_0 < 30$ m/sec, but even in various regions of a flow where the velocities of the solid-phase and gas-phase particles coincide [7]. In these cases, to separate signals from the specific phase one can use the dependence of the amplitude of the Doppler's signal on KD, where the parameter $K = \frac{2\pi}{\Lambda}$ and Λ is the period of the interference pattern formed in the region of intersection of two coherent laser beams. For a specific ratio of the period Λ and particle size D, the amplitude of the Doppler's signal reaches a minimum [9], which in several cases makes it possible to determine particle size [10].

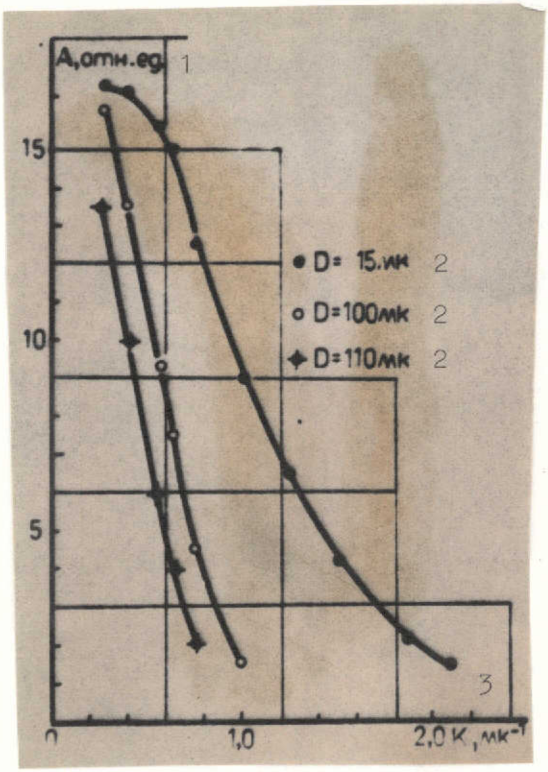

Fig. 3. Dependence of signal amplitude on parameter K for various particle sizes
Key: 1. Relative units
2. μm
3. μm^{-1}

Fig. 3 shows dependence of the amplitude of the Doppler signal on K, experimentally determined, for particles with mean size 15, 100, and 110 μm. Similar functions were found for all fractions used in the study. Analysis of the experimental curves made it possible to determine for each fraction the range of K values in which separation of the Doppler signal is possible. This fact opens up the possibility of investigating the characteristics of motion of just the gas phase in a two-phase flow by introducing into the flow particles of smoke or another impurity with a particle size distribution function that does not coincide with that of the principal fraction. When the period of the interference pattern Λ is suitably selected, it is possible to observe signals either from both phases or from just the label particles simulating the passage of the gas flow. The signal from the principal fraction will be present in the latter case as a constant background degrading the signal-to-noise ratio. The corresponding appearance of the spectra of Doppler signals is in Figs. 4 and 5. In the first case it appears possible to directly determine the slip velocity of the solid fraction from the displacement of the maxima of the Doppler signals from both phases. In the second case, it is possible to determine the averaged and pulsational characteristics of just the gas phase of the two-phase flow, using various types of servo systems [11] or spectral analysis of the Doppler signal [12].

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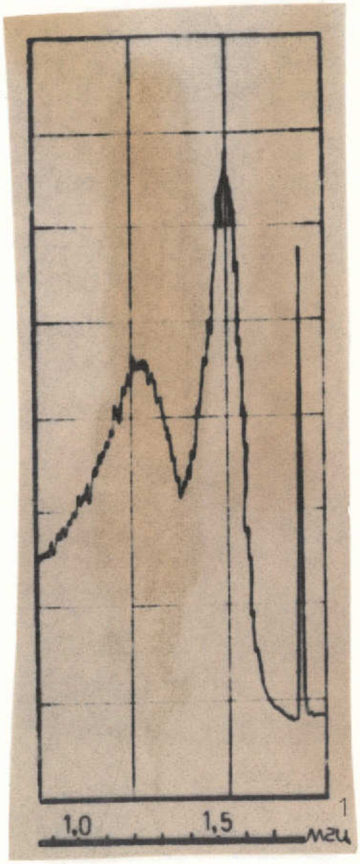

Fig. 4. Spectrum of Doppler signal from mixture of particles of size 100 μm (f = 1.23 MHz) and 5 μm (f = 1.55 MHz) for K = = 0.8 μm^{-1}
Key: 1. MHz

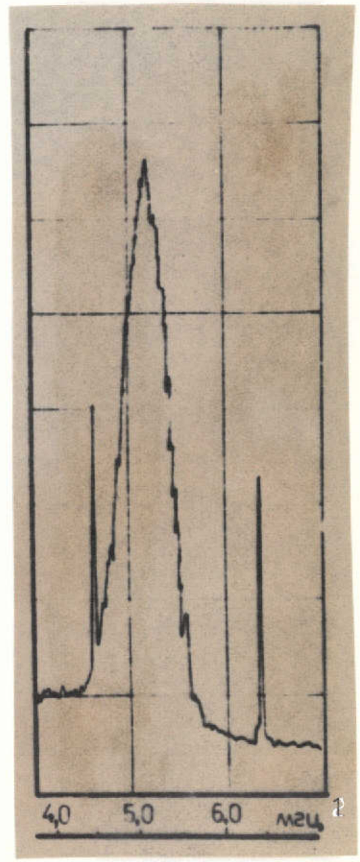

Fig. 5. Spectrum of signal from mixture when K = 1.6 μm^{-1}
Key: 1. MHz

The experimental setup (Fig. 6) was mounted on a modified version of the LDIS [7]. A beam of light from a LG-36A laser was split by block (2) into two equal-intensity beams, which were focused with lens (3) at the test point of the flow. In measuring the distribution profiles of the relative concentration, the beam $\vec{K}_2$ overlapped, and the beam $\vec{K}_1$ passed along the flow, diaphragm, and neutral filter (10) and impinged at the photodetector PD 3. Model FEU-51 photoelectric multipliers served as the photodetectors. The detection system of the LDIS (5, 12) was used to record the

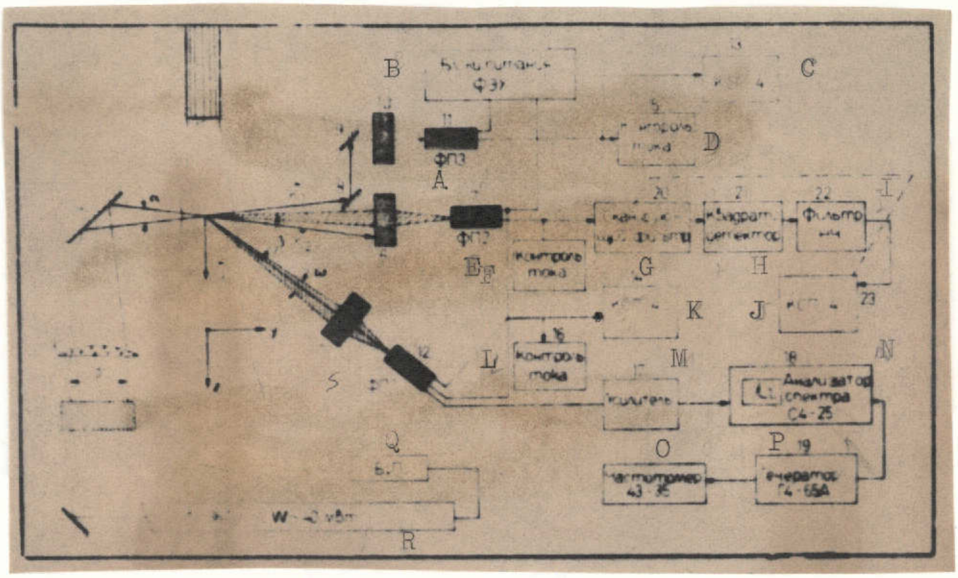

Fig. 6. Scheme of experimental setup
Key: A. PD 3
B. Photoelectric multiplier power block
C. Illegible
D. Current monitor
E. PD 2
F. Current monitor
G. Scanning filter
H. Square-law detector
I. Low-frequency filter
J. Illegible
K. Illegible
L. Current monitor
M. Amplifier
N. S4-25 spectral analyzer
O. 43-5 frequency meter
P. G4-65A signal generator
Q. Illegible
R. Illegible
S. PD 1

scattered light. It was placed in this scheme at the angle $\beta = 20°$ to the bisector of the angle of beam intersection $\alpha \approx 2°$. The voltage picked off from the load of the photodetectors (11, 12) was fed to the recording potentiometers (13, 14). The photoelectric multiplier current was monitored with microammeters (15, 16). The circuit linearity was checked with neutral light filters. In measuring the phase velocities, the signal from PD 1 (12) was amplified with a wide-band amplifier (17) and observed on the screen of the spectral analyzer (18). A signal generator (19) was used to obtain the frequency markers. The period of the interference pattern was varied with focusing lenses (3) with different focal lengths. The parameters of the interference pattern were calculated using formulas proposed in [13]. Spectra of the Doppler signals were recorded with a system made up of a scanning narrow band filter (20), square-law detector (21), low-frequency filter (22), and recording potentiometer (23). A model V6-1 selective microvoltmeter served as the scanning narrow band filter; the scanning rate was synchronized with the recorder tape travel rate. In recording this spectra, the detection system of the LDIS (6, 7), analogous to (5, 12), was oriented with respect /390 to the bisector of angle α. The size of the volume of data extraction with respect to axes x, y, and z was 0.6 x 1.6 x 0.6 mm.

The above-described equipment in principle makes it possible to obtain all the necessary data on the averaged characteristics of two-phase "gas-solid particle" flows.

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